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SPECTRAL GAMMA-RAY LOGGING III: FORMATION AND THIN BED EFFECTS

by

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ABSTRACT

The effect of borehole formation parameters on spectral gamma-ray probe response has been calculated from radiation theory. Results are presented for the effect of formation bulk density and composition on the gamma-ray spectra from potassium, uranium, and thorium.

Experimentally determined response functions are presented for spectral gamma-ray probes logging through thin horizontal beds of potassium, uranium, and thorium. Potassium and thorium thin bed results were obtained by numerical differentiation of the probe response across the interface between a thick zone containing potassium or thorium and a thick barren zone. Uranium results were obtained both from differentiation of thick zone interface measurements and directly using thin bed uranium models. All measurements were performed at the U. S. Department of Energy (DOE) calibration facility in Grand Junction, Colorado, using sodium iodide detectors of various sizes.

Detector size and shape was found to have a larger effect on the thin bed response function than did the formation parameters which can affect the transport properties of the gamma rays. Results have been used to deconvolve observed borehole logs and obtain concentration with depth for thin ore zones.

INTRODUCTION

The quantitative determination of potassium, equivalent uranium or thorium concentration from spectral gamma-ray borehole logs may require corrections for differences in composition between the models used for calibration and the formations encountered in the field. These compositional differences are mainly in the formation's matrix and its moisture content, and they affect the gamma-ray transport through the formation. The importance of these factors on calculated concentrations is most easily determined through computer studies because the construction of adequate physical models is extremely difficult and prohibitively expensive. Consequently, the transport of gamma rays through infinite media of different matrix and moisture conditions has been calculated using computer codes.

When the sources of gamma rays are in the form of thin beds, the signal observed within a borehole can not be directly interpreted with infinite media calculations or experimental calibration data collected on models with thick beds. It is necessary to know the probe's response to an infinitesimally thin bed and then deconvolve the observed borehole log to obtain concentrations along the borehole axis. Computer calculations for thin beds are more difficult than are calculations for infinite media. Fortunately experimental data from thin beds can be collected using physical models at Grand Junction, Colorado. Data from these models provide thin bed response functions for deconvolution of borehole logs from layered uranium media.

FORMATION EFFECTS ON GAMMA-RAY SPECTRA

Gamma-Ray Spectral Calculations

Gamma-ray transport calculations have been performed (References 1-3) at the Los Alamos Scientific Laboratory (LASL) in an effort to quantify the formation effects. Gamma-ray flux spectra were computed for sandstone and shale and for a variety of water-saturated porosities using gamma rays from the naturally radioactive isotopes of potassium, equilibrium uranium, and thorium. The source gamma rays used as input to the calculations are shown in Figure 1 along with their relative intensities. The gamma rays appear as sharp lines with no background continuum because formation scatter and detector broadening are not present. The LASL discrete ordinates transport code ONETRAN (Reference 4) was upgraded to perform gamma-ray spectral calculations with 10 keV energy resolution for media of infinite extension. Using the gamma rays in Figure 1 as input to ONETRAN the spectra in Figure 2 were obtained for an idealized sandstone formation with zero porosity. Similar calculations were also performed for shale and for various porosities and water saturations. The spectra in Figure 2 illustrate the excellent energy resolution of the calculations and show that the continuum portion of each spectrum becomes increasingly important at the lower energies. The spectra are those which would be obtained from a "perfect" gamma-ray detector placed within an infinite medium containing uniformly distributed potassium, equilbrium uranium, and thorium sources. Most real detectors will enhance the lower energy regions of the spectra and introduce additional continuum components and peak broadening.

The spectra of Figure 2 should accurately represent the actual gamma-ray energy fluxes for all energies above about 150 keV. For lower energies, the uranium and thorium fluxes are probably somewhat low because X-ray fluorescence for the K-shells of uranium and thorium following photoelectric absorption has not been included in the transport calculations.

Formation Density and Z/A Effect

Gamma rays interact with the atomic electrons of materials through the photoelectric effect, Compton scattering, and pair production. The photoelectric effect varies inversely with the cube of incident gamma-ray

GAMMA-RAY SOURCE ENERGIES AND RELATIVE INTENSITIES FOR BOREHOLE TRANSPORT CALCULATIONS

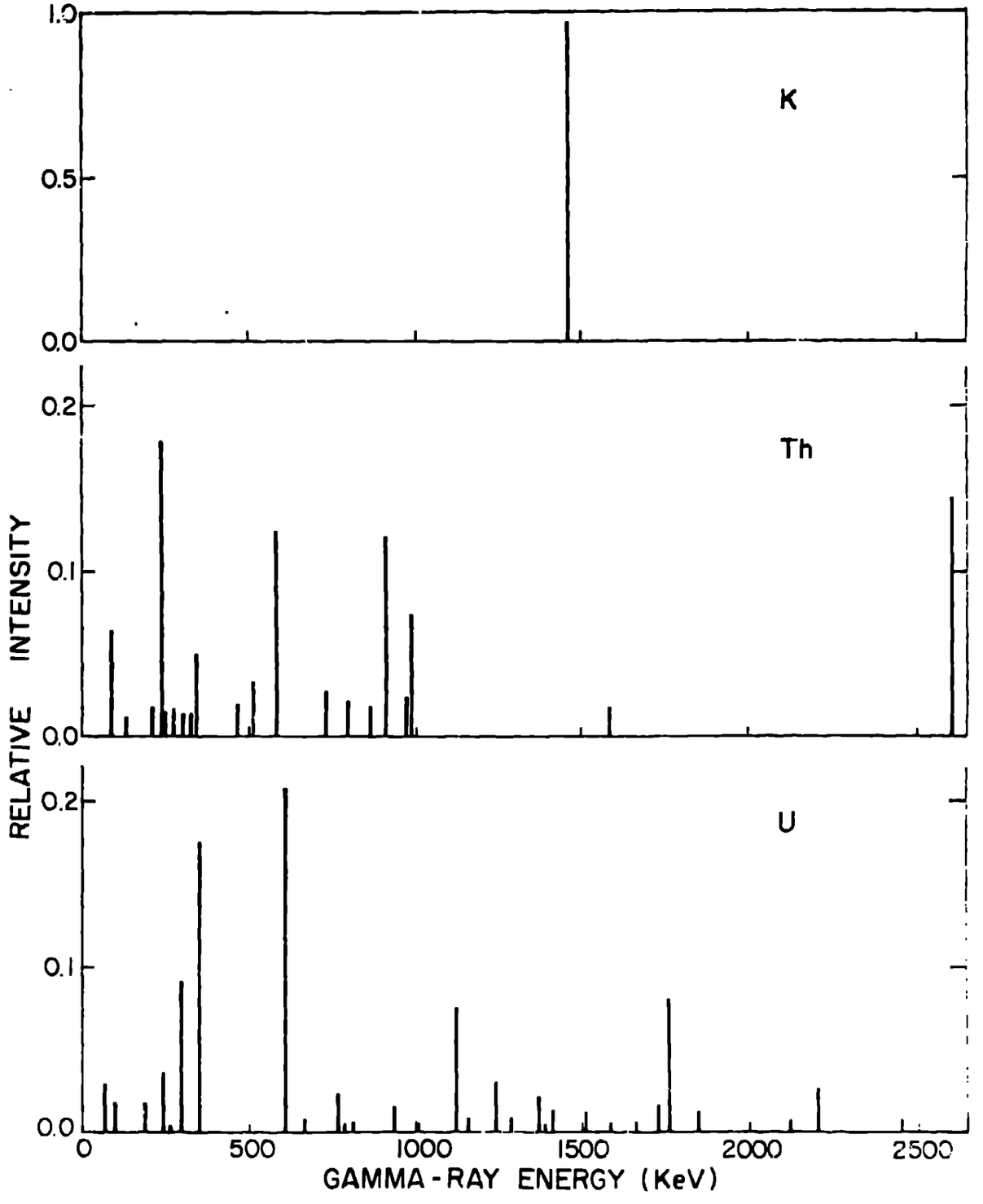
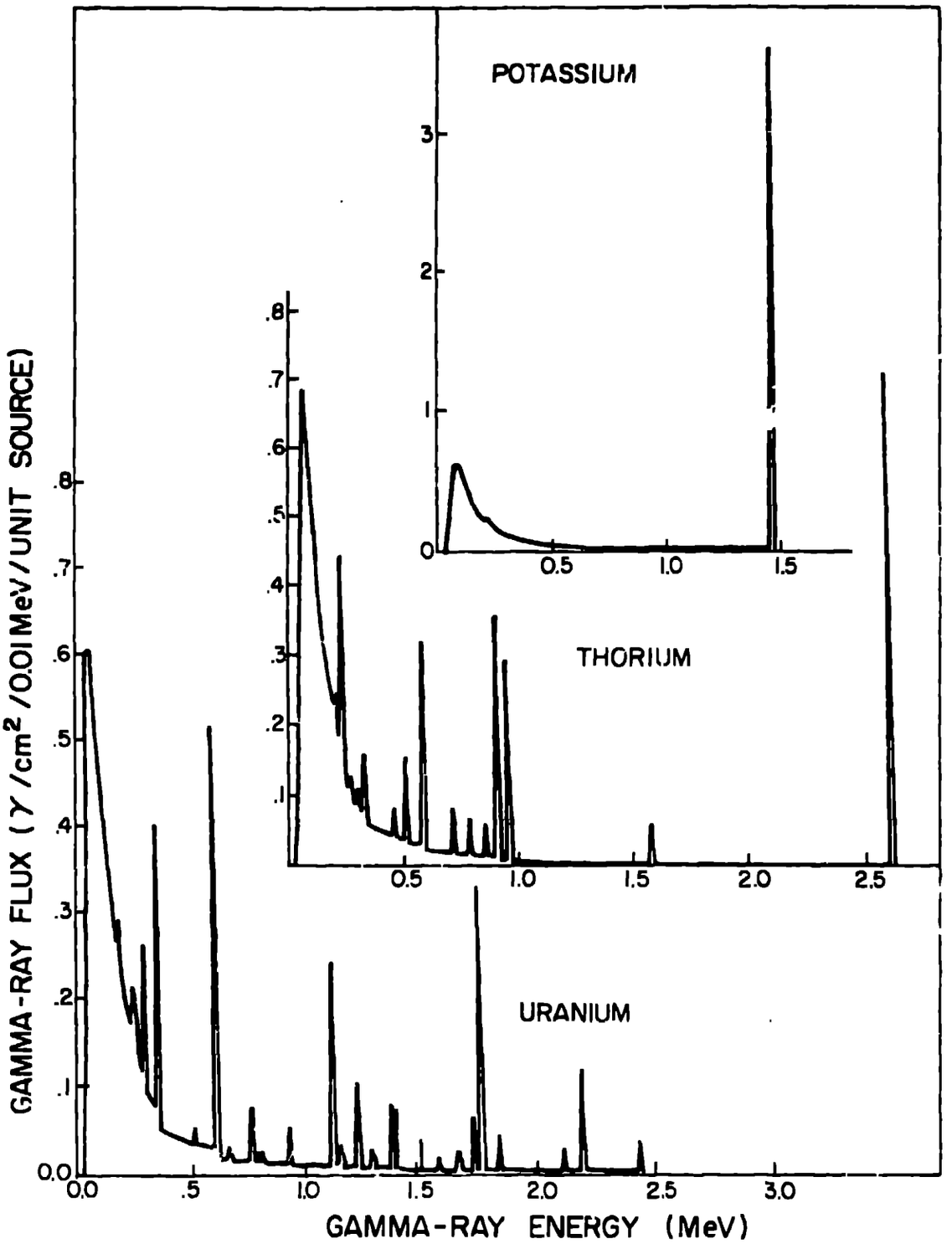


Figure 1



Calculated Spectra For Potassium, Equilibrium Uranium, and Thorium Sources Uniformly Distributed in an infinite Sandstone Medium.

Figure 2

energy and directly as the fourth power of the atomic number (Z) of the material. The Compton scattering probability per atom decreases slowly with increasing gamma-ray energy and varies directly with atomic number. Pair production starts at a threshold of 1.02 MeV, and its probability increases slowly with energy.

For typical geological formations, the average atomic number ranges from 13 to 20. For this range of atomic numbers, Compton scattering dominates the gamma-ray attenuation process over the energy range from 0.1 MeV to 10 MeV. When high grade uranium zones or other materials with large atomic numbers are encountered, the lower limit of this "Compton range" must be raised due to an increased photoelectric effect. The pair production process becomes significant only above 10 MeV and dominates gamma ray attenuation above 15 MeV.

The Compton linear attenuation coefficient for a formation containing a mixture of atomic species can be written

$$\mu_c = \sigma_{ce} N_o \rho_B \left(\frac{\overline{Z}}{\overline{A}}\right), \qquad (1)$$

where σ_{ce} is the Compton scattering cross-section per electron, N_o is Avogadro's number, ρ_B is the formation bulk density, and $(\overline{Z/A})$ is a partial density weighted average value of atomic number divided by atomic mass. Since the Compton scattering mechanism dominates the gamma-ray interaction process for typical formations from energies of 0.1 MeV to 10 MeV, equation (1) indicates that the gamma-ray fluxes should scale inversely with both formation bulk density (ρ_B) and partial density weighted average $(\overline{Z/A})$.

Computer calculations for infinite media have verified that the gamma-ray flux spectra do scale as expected with the inverse of formation bulk density. Calculations have also been performed which test the $(\overline{Z/A})$ dependence by changing the water-saturated porosity in a sandstone formation. The gamma-ray flux was calculated as a function of energy for sandstone with water saturated porosities of 0.1 and 0.3. The ratio of fluxes for the two porosities was found to be constant at a value of 0.875 over the entire energy range of 0.1 2.6 to MeV which is the range of interest to spectral gamma-ray logging. Below this energy, the composition-dependent change in the photoelectric cross-section, which increases strongly with decreasing energy, caused the flux ratio to drop rapidly because of the higher average Z of the 0.1 porosity water-saturated formation. The constant nature of the flux ratio to 2.6 MeV indicates that pair production is unimportant to this problem.

The calculated ratio 0.875 is in agreement with the value predicted by simple inverse scaling with bulk density and average $(\overline{Z/A})$. For the sandstone matrix density of 2.626 g/cm^3 used in the computer calculations and for partial density weighted average $(\overline{Z/A})$ values of 0.499 and 0.551 for sandstone

and water, respectively, the flux ratio predicted by the product of inverse bulk density and $\overline{(Z/A)}$ scaling factors is

$$\text{Flux Ratio} = \frac{(0.499)(0.7)(2.626) + (0.551)(0.3)}{(0.499)(0.9)(2.626) + (0.551)(0.1)} = 0.877 \qquad (2)$$

The result of equation (2) is the predicted flux ratio based on the change in the Compton linear attenuation coefficient. The agreement with the ratio 0.875 determined from actual transport calculations of the gamma-ray spectra is excellent.

Calculations for other water saturated porosities and for a shale rock matrix have also been made. In all cases the agreement between transport calculations and Compton scaling is excellent over the energy range of interest for gamma-ray logging. This shows that Compton scattering dominates the gamma-ray attenuation process. Consequently the effect of formation bulk density and composition-dependent changes in $\overline{(Z/A)}$ on the gamma-ray flux can be accurately computed by the simple scaling technique. The formation's moisture affects the gamma-ray flux mainly through the bulk density. For the example presented in equation (2), the change in formation $\overline{(Z/A)}$ due to the decrease from 30 percent to 10 percent by volume in moisture content leads to a one percent increase in gamma-ray flux while the resulting bulk density increase leads to a 13 percent decrease in gamma-ray flux.

Effect of Elements with Large Atomic Numbers

The effect of a high concentration of elements with large atomic numbers, such as uranium (Z=92), has been considered. Energy dependent flux ratios have been computed for uranium concentrations of 0.06, 0.2, 0.6, 2.0, and 6.0 percent uranium, by weight. Results for 0.06, 0.6, and 6.0 percent uranium are shown in Figure 3. The flux ratios in the figure were formed by computing the flux spectrum at the stated uranium grade and dividing by the result for the same gamma-ray source strength (Figure 1), but for a transport formation free of the element uranium. Formation bulk density was held constant throughout. For uranium grades less than or equal to 0.6 percent, the flux ratio is nearly unity from 1.0 to 2.6 MeV but it begins to drop at lower energies. For 0.6 percent uranium, the flux ratio drops to about 0.95 at 0.3 MeV. For uranium grades below 0.6 percent and for energies greater than 0.5 MeV, the flux ratio is unity to within 1 percent. For uranium grades above 0.6 percent the effect of uranium content is increasingly important at the low energies. For the 6 percent case, the flux ratio at 0.3 MeV is aproximately 0.7, which corresponds to a 30 percent drop in the gamma-ray flux. Above 0.3 MeV, the flux ratio for 6.0 percent uranium never reaches a constant value with increasing energy. This means that the photoelectric effect and/or pair production are important processes, in addition to Compton scattering, for the entire energy range of interest. Probes calibrated in models with low concentrations of high atomic number elements will predict inaccurate concentrations in formations which contain several percent by weight of high atomic number elements.

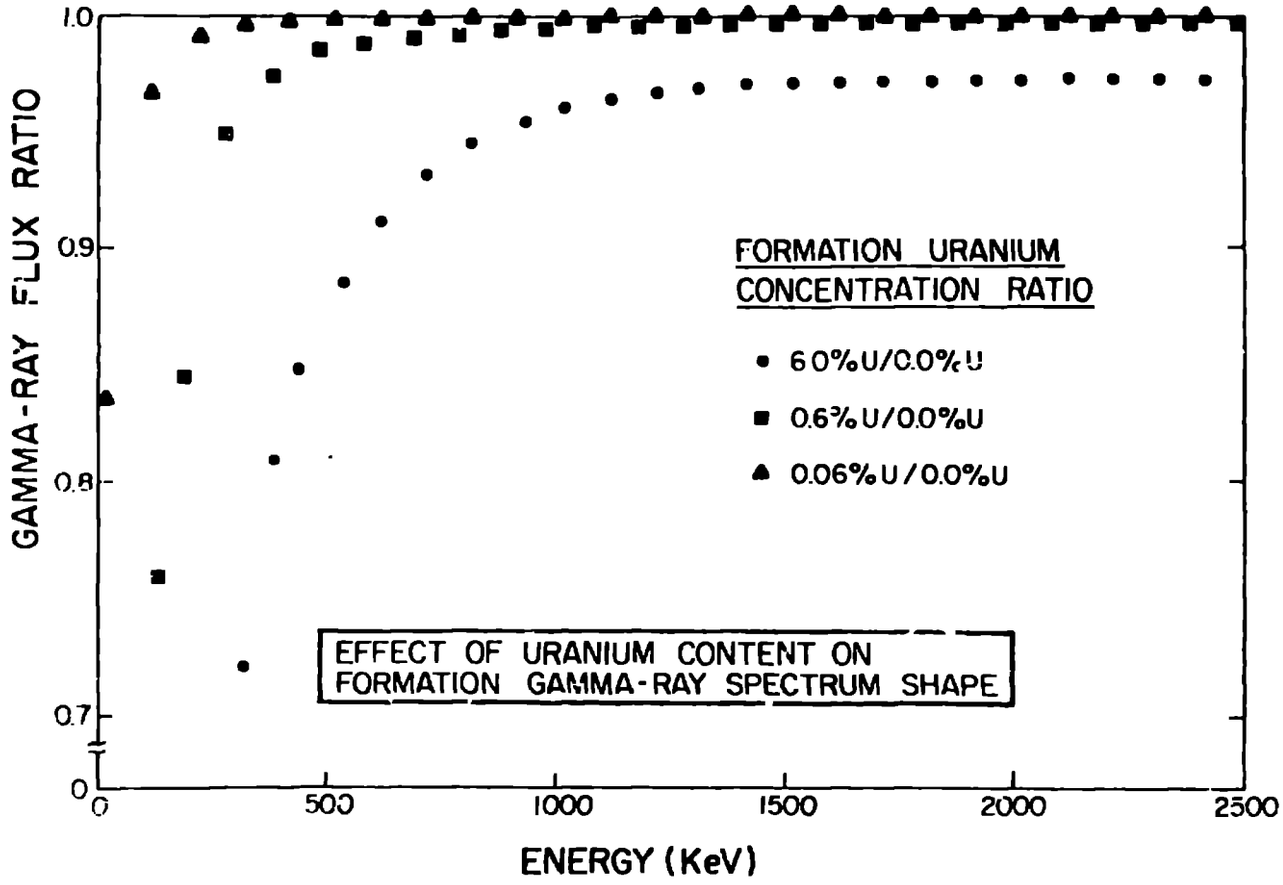

GAMMA-RAY FLUX RATIO
1.0
0.9
0.8
0.7
0
0
500
1000
1500
2000
2500
ENERGY (KeV)
FORMATION URANIUM
CONCENTRATION RATIO
6.0%U/0.0%U
0.6%U/0.0%U
0.06%U/0.0%U
EFFECT OF URANIUM CONTENT ON
FORMATION GAMMA-RAY SPECTRUM SHAPE

Figure 3

Summary of Formation Effects

The infinite media gamma-ray transport results have led to the following conclusions concerning formation corrections to spectral gamma-ray logs:

1. For virtually all formations of interest (average atomic number from 13 to 20) the Compton scattering process is the only significant gamma-ray attenuation mechanism for energies between 0.1 and 2.6 MeV.

2. The gamma-ray flux at any energy within this range will scale inversely with the formation bulk density and with the formation $\overline{(Z/A)}$.

3. The formation $\overline{(Z/A)}$ varies little from the nominal value of 0.500. Usually the largest changes in $\overline{(Z/A)}$ are caused by variations in formation moisture content, but even the largest practical variations in moisture content yield less than a 2 percent change in $\overline{(Z/A)}$ for the formation.

4. For the energy range of interest in spectral gamma-ray logging, the effect of formation compositional changes on gamma-ray flux is well described by a simple inverse bulk density scaling.

5. Given a certain gamma-ray source per unit volume from either potassium, equilibrium uranium, or thorium, the percent concentration by weight scales inversely with any increase in bulk density due to additions of other constituents, such as moisture. Since the gamma-ray flux also scales with the inverse of bulk density, the gamma-ray flux characteristic of a given element will always be proportional to the concentration, by weight, for the element, regardless of bulk density.

6. Spectral gamma-ray field logs can be used to calculate concentrations in percent or ppm by weight without knowledge of the formation's moisture content, if the same moisture content is assumed to exist in both the calibration models and the field formations. The error introduced by making this assumption is related to $\overline{(Z/A)}$ and it generally amounts to only about one percent.

7. Concentrations of elements with large atomic numbers (including uranium) do not affect gamma-ray transport for the energy range from 0.5 MeV to 2.6 MeV provided their concentrations are less than 0.6 percent. For higher concentrations the gamma-ray flux at the lower energies become increasingly attenuated, and at 6 percent uranium concentration the flux is attenuated by approximately 30 percent at 0.3 MeV. However, for the energy range from 1 to 2.6 MeV, which is of particular interest to spectral gamma-ray logging, the flux at 6 percent uranium is attenuated by only 3 percent.

THIN BED PROBE RESPONSE

The Geologic Impulse Function

When spectral gamma-ray probes pass through thin ore zones, their response to the sharp zone transitions is smoothed both by the finite length of the probe's detector and by the penetration of gamma rays from the ore zone into adjacent barren zones. In order to reconstruct the true characteristics of thin zones from gamma-ray logging data, the "thin bed response" of the detector must be determined. This response depends on the source gamma-ray energies, the formation through which the gamma rays must travel, the borehole conditions, and the probe's detector.

For infinitesimally small detectors the theoretical work by Czubek (Reference 5) predicts that the response function is a two-sided exponential of the form

$$I(z) = \frac{\alpha}{2} \exp(-\alpha|z|) \tag{3}$$

where I(z) is the observed thin bed response as a function of position z from the bed, and α is the parameter that determines how rapidly the response falls off with z. The factor $\alpha/2$ is required for unity normalization of the function I(z). Equation (3) has been used recently by Conaway (Reference 6) in a new approach to gamma-ray log deconvolution (zone reconstruction) that utilizes the principles of Digital Time Series Analysis. Conaway calls the thin bed function of equation (3) the geologic impulse function. The thin bed measurements presented in this paper will be analyzed for the geologic impulse parameter α and then applied to an example of the log deconvolution problem.

When the effect of finite detector length is included, the response function becomes more complicated (Reference 7):

$$I(z) = \begin{cases} \frac{1}{L} \sinh \frac{\alpha L}{2} \exp(-\alpha|z|) & \text{for } |z| \geq \frac{L}{2} \\ \frac{1}{L}\left[1-\cosh(\alpha z)\exp(-\alpha L/2)\right] & \text{for } |z| < \frac{L}{2} \end{cases} \tag{4}$$

where L is the detector's length.

Measurement of the Geologic Impulse Parameter α

The parameter α in the geologic impulse function of equation (3) can be determined by direct experimental measurement. The most precise data are obtained if probe response is measured through a thin zone of the radioactive species of interest (potassium, equilibrium uranium, or thorium). A "thin zone" is one whose thickness is less than half the detector's length. If thin zones are not available, the parameter α can be determined by measuring the probe's response across a plane interface between a homogeneous ore zone and a barren zone. Both zones must be at least two feet thick to approximate semi-infinite media.

Calculations have been performed by Czubek (Reference 8) that predict the value of α for various values of the gamma-ray linear attenuation coefficient and borehole diameter. These calculations apply only to unscattered, unattenuated gamma rays from a cylindrical source and they assume an

infinitesimally small detector in a dry borehole. The measured α values presented in this paper will be compared to the calculations of Czubek.

Ore Zone/Barren Zone Interface Results

A thin zone model is available at Grand Junction, Colorado for uranium, but not for potassium or thorium. Therefore, ore zone/barren zone interface profiles were required to obtain α for the potassium and thorium signals. Profile measurements were performed in calibration models for probes containing 1.5 inch diameter sodium iodide detectors with lengths of 3 and 9 inches.

Potassium (K) model profile results are plotted in semilogarithmic form in Figures 4 and 5 for the 3 and 9 inch detectors, respectively. The apparent grades were obtained from count rates in energy windows for each detector using the thick zone matrix calibration technique (Reference 9). These data were fit with smooth curves and numerically differentiated to yield the equivalent of a thin potassium bed response function. Figures 6 and 7 are semilogarithmic plots of differential potassium grade for each detector length. These curves represent the geologic impulse functions for a potassium source in a concrete medium with a dry 4.5 inch diameter borehole and for the 3 and 9 inch detector lengths. The shorter detector exhibits an impulse function that is narrower by 9 cm at full width at half maximum (FWHM) and by only 2 cm at full width at tenth maximum (FWTM). Also, the maximum apparent differential grades occur as expected at the interface between the two zones, and the observed maximum is higher for the short detector.

The geologic impulse parameter α can be obtained from the differential curves in Figures 6 and 7. Equation (4) shows that the predicted geologic impulse function for a detector of length L falls off exponentially with decay constant α for $|z| \geq L/2$. The semilogarithmic plots are in fact nearly linear for these regions above and below the interface. The slope computed from straight line fits in these regions gives the value of α directly. These values are given on the figures and in Table 1 as "measured α".

The geologic impulse response function represented by equations (3) and (4) predicts that α is independent of detector length. The theoretical calculations of Czubek (Reference 8) were applied to obtain α values for the 1.46 MeV potassium gamma ray in the concrete medium of both the barren zone and the ore zone. The results are given in Table 1 as calculated α. α is calculated to be larger in the barren zone because of its higher bulk density.

The calculated values are in good agreement with the measured α for the 1.5 inch x 3 inch crystal. However, the 1.5 inch x 9 inch crystal yields a higher measured α than a calculated α. Apparently α depends on detector shape. Perhaps this dependence is caused by a decreasing detector sensitivity for gamma rays incident on its end. Since the fraction of incident gamma rays directed at the end of the detector increases with increasing distance from a thin source layer, the result is a drop in count rate with a resulting apparent increase in the constant α for the impulse function.

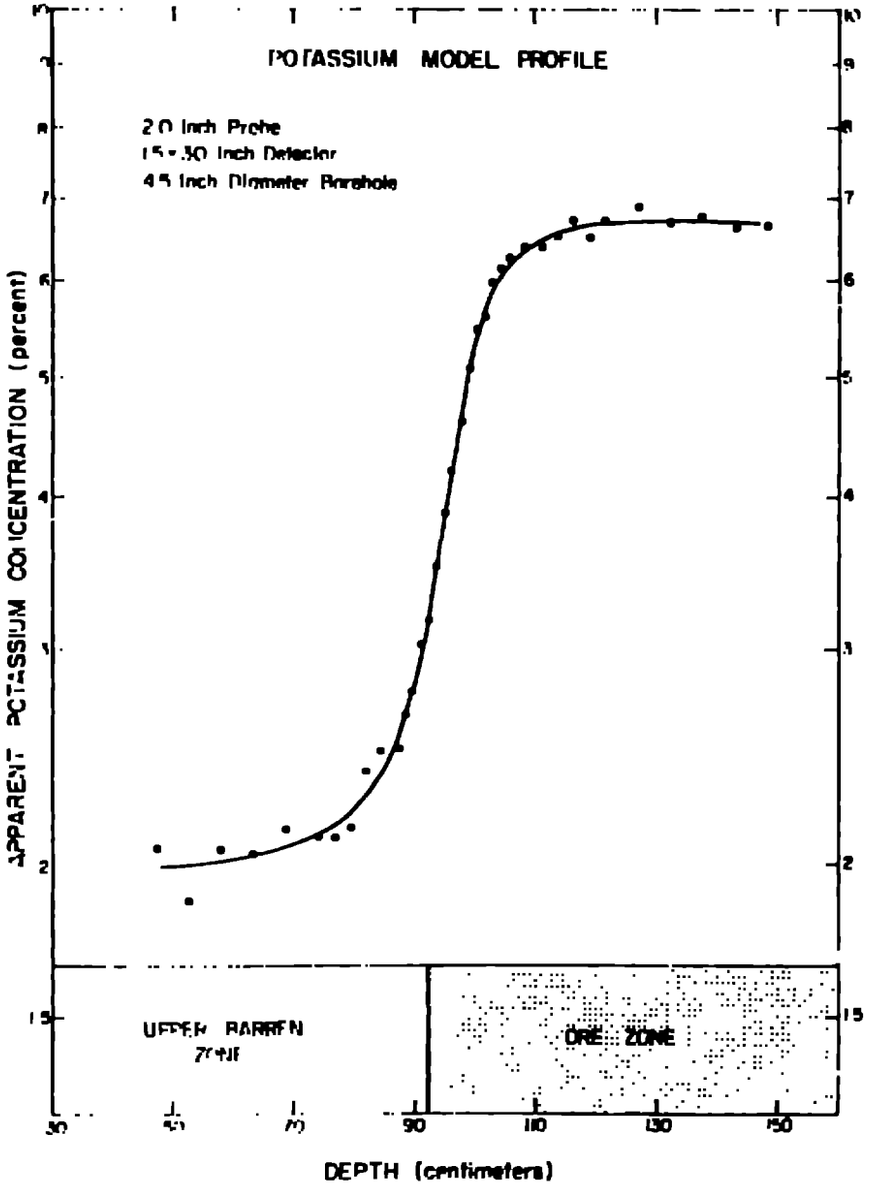


Figure 4

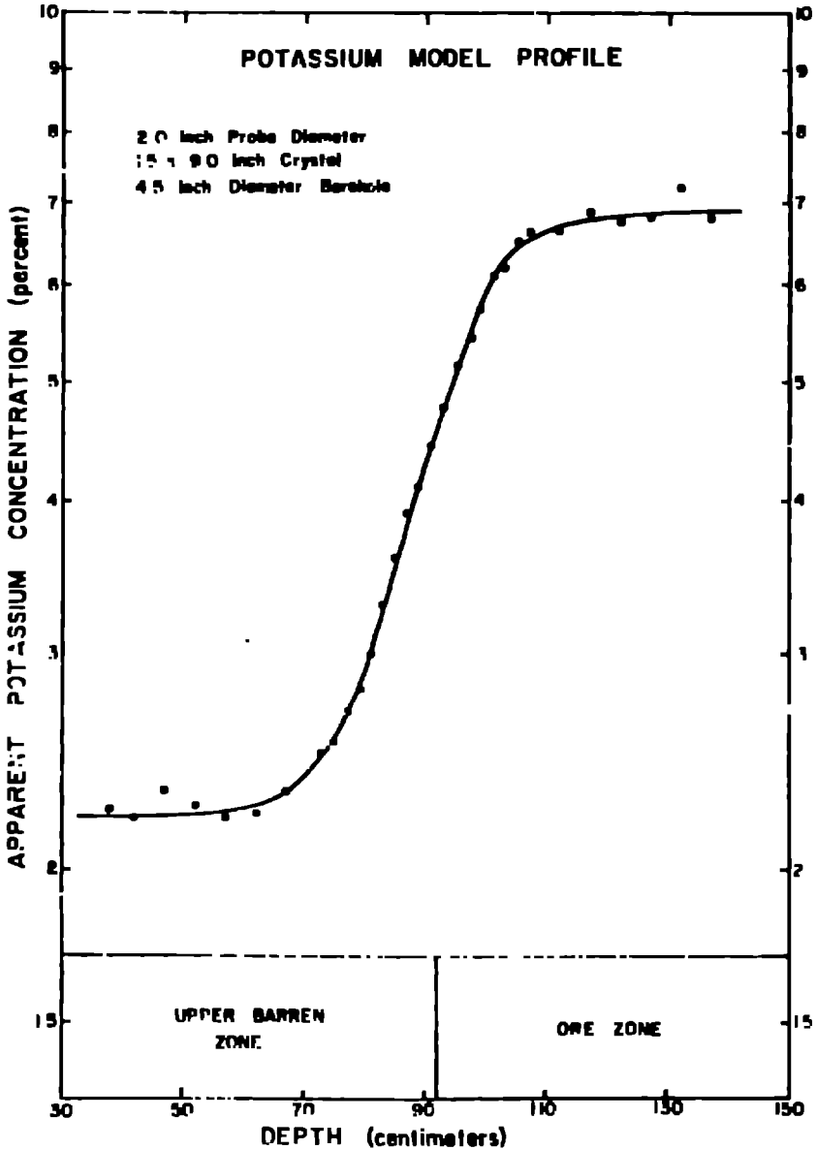


Figure 5

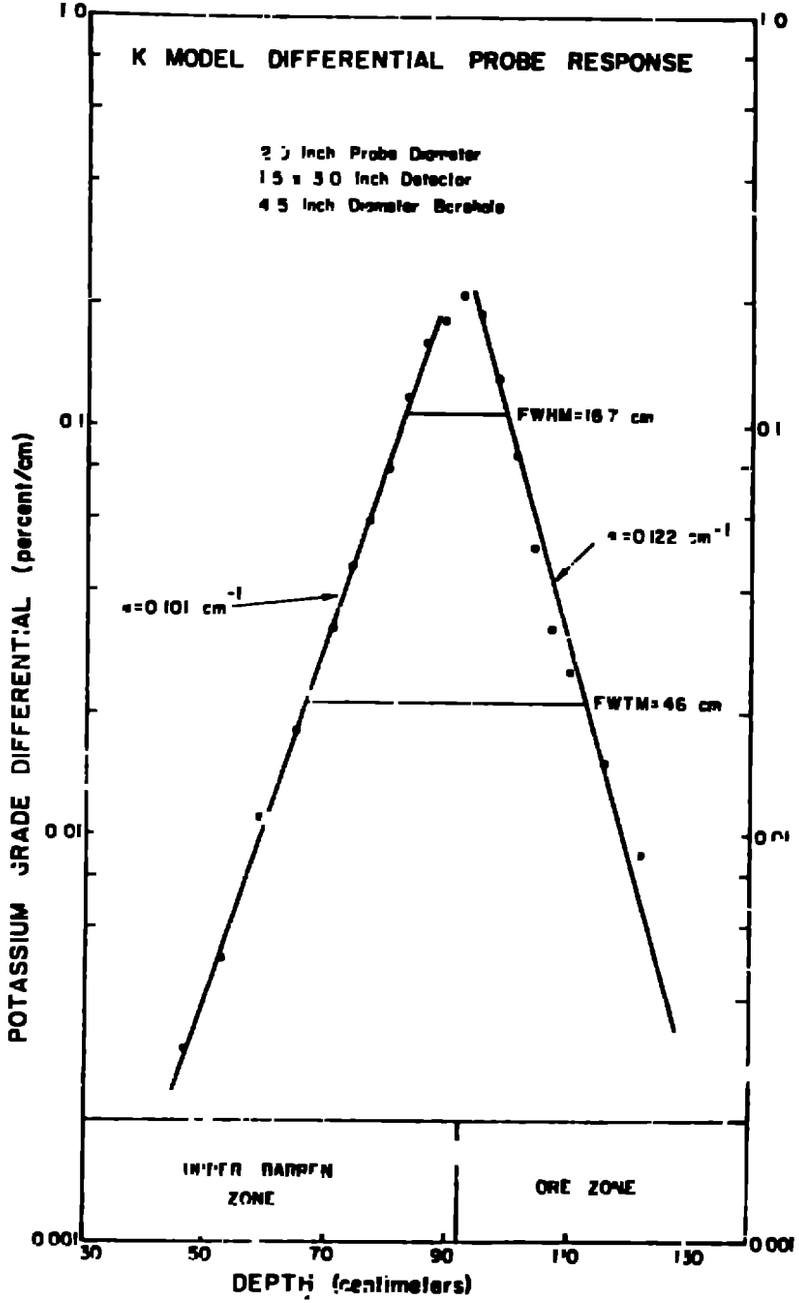


Figure 6

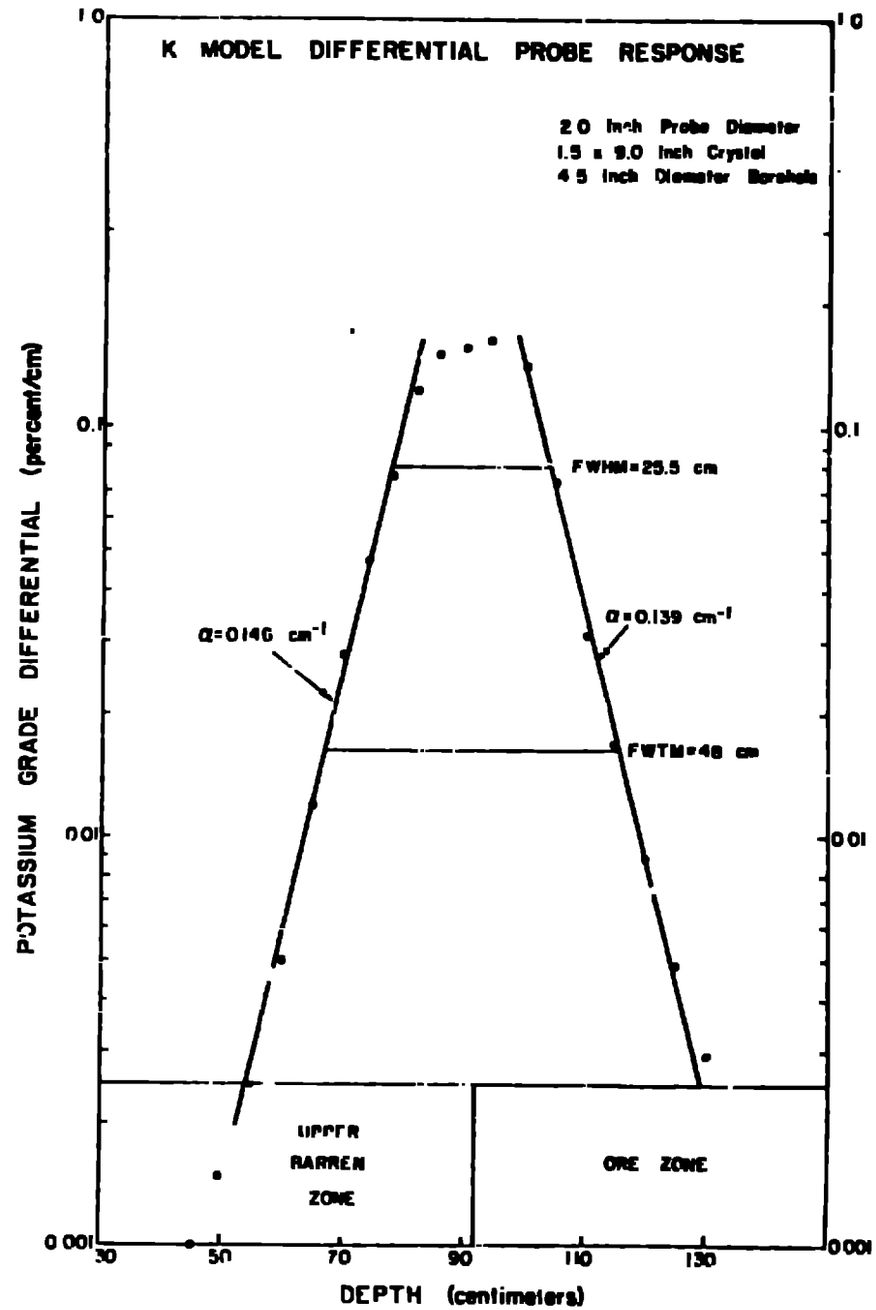


Figure 7

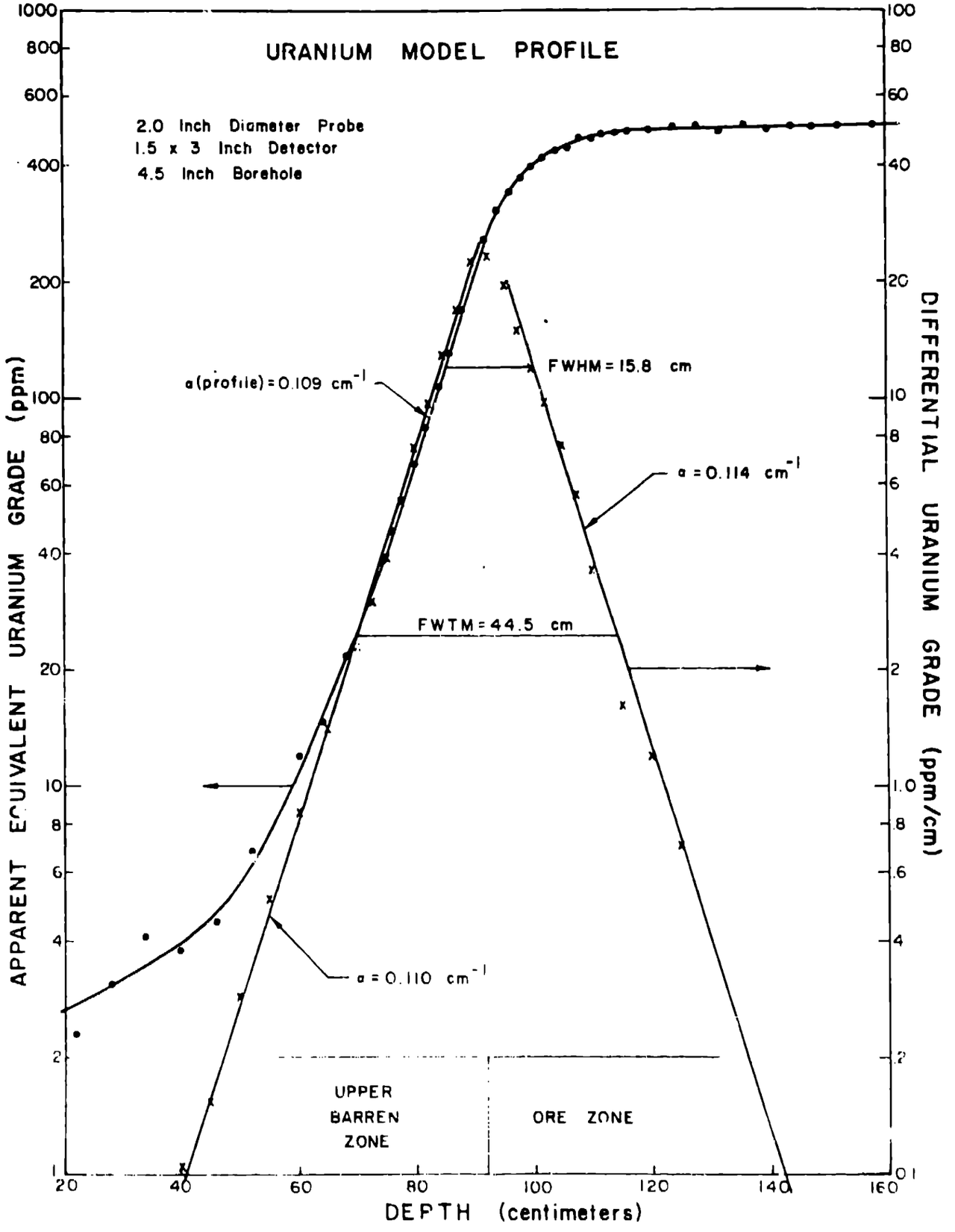
Profile results for the thick zones of the uranium (U) model are presented in Figure 8 for a 3 inch detector. Following the same procedure as with the K model, differential uranium grades were computed and they are plotted as "X's" in the figure. Note that the linear portion of the profile (dots) is almost coincident with the differential data (X's) in the barren zone. This will happen whenever one of the two regions forming the interface is truly barren. This was not the case for the K model but is nearly true for the U model. The $\alpha(0.109\ cm^{-1})$ obtained from the depth profile in Figure 8 is slightly lower than the average value ($0.110\ cm^{-1}$) obtained from the corresponding differential grade plot because the "barren" zone is not truly barren of uranium. Although profile α values are much easier to determine because numerical differentiation is not required, the differential grade function data yield more accurate α's.

Measured and calculated α's for the uranium and thorium models are summarized in Table 1. Comparing measured detector α's for the 3 and 9 inch detector lengths, the longer detector consistently yields larger α values for the barren zone region of the K, U, and Th models. This is because the gamma-ray flux is becoming more highly directed along the detector's axis as the probe moves away from the interface into the barren zone. When the detector is in the ore zone, the gamma-ray flux is more isotropic, and hence the angular sensitivity differences between a long and short detector are not so important to the measurement. Thus, within the ore zones, measured α values are not very different for the two detector lengths.

Thin Uranium Bed Results

Interface profile measurements of the type presented in the previous section are difficult to perform because they are tedious and time-consuming, especially for small detectors. Furthermore, the calculations required to determine the differential shape introduce noise on the geologic impulse function.

Better results are obtained when thin beds of the radioactive material are available. Thin beds of potassium or thorium are not available, but a 2 inch thick uranium bed perpendicular to a borehole exists at Grand Junction. This thin bed was used to measure the uranium geologic impulse function for several detector sizes and borehole conditions. Results of logging the thin uranium bed with a 1.5 inch diameter x 3 inch long sodium iodide detector are given in Figure 9. The data were collected for a dry, 4.5 inch diameter borehole through the thin zone in a dry condition, and the results have been corrected for the 3.5 ppm uranium content in the barren zones on each side of the thin bed. α values of $0.095\ cm^{-1}$ and $0.099\ cm^{-1}$ were obtained from the slope of linear portions of the semilogarithmic data plot. These values are presented in Table 1 along with results for other detectors, probe diameters, and borehole conditions. Also given in the table is the theoretical α value of $0.104\ cm^{-1}$ calculated from the work of Czubek.


URANIUM MODEL PROFILE
2.0 Inch Diameter Probe
1.5 x 3 Inch Detector
4.5 Inch Borehole
α(profile) = 0.109 cm⁻¹
FWHM = 15.8 cm
α = 0.114 cm⁻¹
FWTM = 44.5 cm
α = 0.110 cm⁻¹
UPPER BARREN ZONE
ORE ZONE
APPARENT EQUIVALENT URANIUM GRADE (ppm)
DIFFERENTIAL URANIUM GRADE (ppm/cm)
DEPTH (centimeters)
1000
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1
100
80
60
40
20
10
8
6
4
2
1.0
.8
.6
.4
.2
.1
20
40
60
80
100
120
140
160

Figure

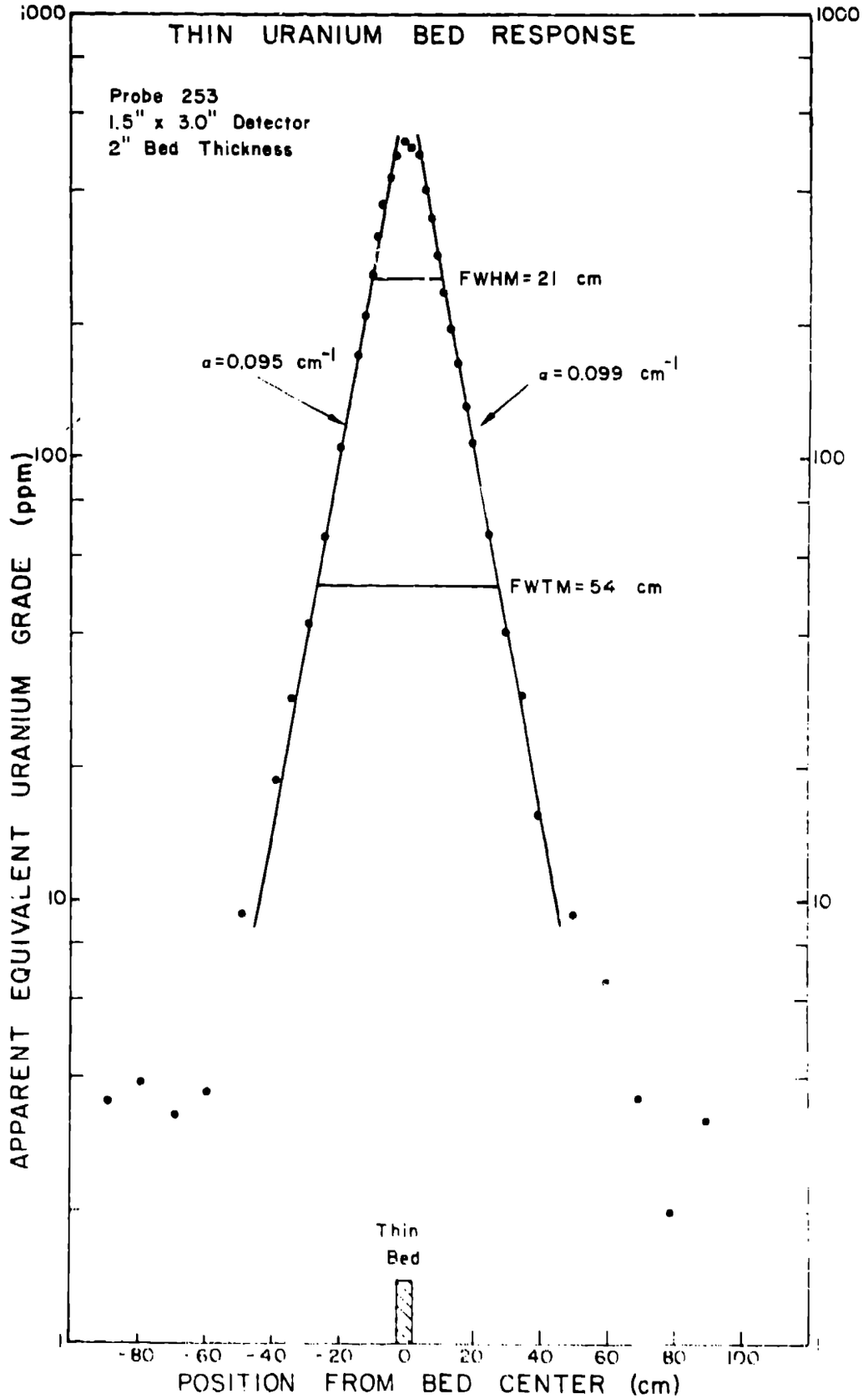

THIN URANIUM BED RESPONSE
Probe 253
1.5" x 3.0" Detector
2" Bed Thickness
FWHM = 21 cm
α = 0.095 cm⁻¹
α = 0.099 cm⁻¹
FWTM = 54 cm
Thin Bed
APPARENT EQUIVALENT URANIUM GRADE (ppm)
POSITION FROM BED CENTER (cm)
1000
100
10
1
-80
-60
-40
-20
0
20
40
60
80
100

Table 1. Geologic Impulse Parameter α

Gamma Ray Signal Window(keV)	Measurement Type	Detector Size (Inches)	4.5 Inch Borehole Condition	FWHM (cm)	FWTM (cm)	Parameter α (cm^{-1}) Measured		Calculated	
						Ore Zone	Barren	Ore Zone	Barren
Potassium (1320-1575)	K Model Differential	1.5 x 3	Dry	16.7	46	0.122	0.101	0.102	0.113
	Profile	1.5 x 9	Dry	25.5	49	0.139	0.146		
Uranium (1650-2390)	U Model Differential	1.5 x 3	Dry	15.8	44.5	0.114	0.110	0.116	0.108
	Profile	1.5 x 9	Dry	26.9	53.3	0.115	0.131		
						(+)	(-)	0.104	
	Thin	1 x 2	Dry	16	47	0.107	0.110		
	Horizontal	2 x 5	Dry	19	47	0.112	0.111		
	U Bed	2 x 5	Water Filled	19	44	0.123	0.124		
		1.5 x 3	Dry	21	54	0.095	0.099		
		1.5 x 9	Dry	25	53	0.118	0.114		
						Ore Zone	Barren	Ore Zone	Barren
Thorium (2475-2765)	T Model Differential	1.5 x 3	Dry	16	44.7	0.123	0.104	0.089	0.096
	Profile	1.5 x 9	Dry	25	49	0.120	0.155		

I terpretation and Summary of Measurements

Measured and calculated values of the geologic impulse parameter α for several detector sizes and for the K, U, and Th window signals have been summarized in Table 1. The table also contains the values of full-width at half-maximum (FWHM) and full-width at tenth-maximum (FWTM) for all measured impulse functions. In all cases measured α's were determined from the linear portion of the semilogarithmic plot of the geologic impulse function. For the differential profile measurements, the linear portions occurred either in the ore zone or in the upper barren zone. For the thin bed measurements, the linear regions are designated in the table as positive (+) or negative (-) distances either side of the thin bed location within identical barren zones of water-saturated sand. For a given gamma-ray signal, the differences in calculated α's are caused by the differences in reported bulk densities. If all bulk densities and compositions were identical, then calculated α's would be identical for a given signal window, and they would systematically decrease from potassium to uranium to thorium.

Measured α's do not follow the variations predicted by the calculations. For example, the measured α's for the thorium signal are comparable to those observed for the potassium signal; and measured values are often lower in the higher density zones, in disagreement with calculation. Certain trends are apparent, however. For a given detector diameter, and for the thin bed or barren zone differential profile measurements, measured values increase with increasing detector length. α's measured within ore zones of the K, U, and Th models using the differential profile technique do not exhibit this dependence on detector length. These results are most likely caused by the strong angular sensitivity of the longer detectors which is more significant for thin zone and barren zone measurements than it is for the ore zones. Thus, the detector shape and resulting variations in angular sensitivity seem to play an important role in determining α, perhaps more important than the transport properties of the gamma rays themselves.

The variation in uranium-to-potassium stripping ratio has been determined for a 1.5 inch x 9 inch detector as a function of distance from a thin uranium ore zone. This stripping ratio specifies how many counts must be subtracted from the K window signal due to the presence of a given number of U window counts and it is an important quantity in the analysis of KUT logs. The stripping ratio reached its minimum value of 0.97 near the thin bed center and increased to about 2.0 at a distance of ± 70 cm from the thin bed. The change in stripping ratio can be explained by the fact that as the detector proceeds away from the thin bed, the intervening attenuating medium (wate saturated sand) causes a build-up of lower energy radiation which causes the tripping ratio to increase. The stripping ratio at the center of the thin bed is actually lower than the value for the thick bed case (1.02) because its scattered component is less. However, for the range of distances containing over 90 percent of the thin bed signal, the stripping ratio changes by only 2 percent. This means that the analysis of KUT logs for thin, layered zones will not require adjustments of the stripping ratios.

A comparison of results in Table 1 for the 2 inch x 5 inch detector shows that the thin bed response function is narrowed by the presence of water in the borehole. Although the FWHM is 19 cm for both dry and water-filled boreholes, α increases by about 10 percent and hence the FWTM is smaller by 3 cm for the water-filled case. The integral thin bed response has also been calculated by summing the response over the range $\pm$ 40 cm for both dry and wet boreholes, and a ratio of dry/wet counts equal to 1.14 was obtained. This ratio compares favorably to a water factor correction of 1.17 obtained from thick zone measurements in the Grand Junction KUT water factor model. It appears that thick zone water factor corrections will be adequate for thin, layered potassium, uranium, or thorium formations.

The variations in measured α values for the various detector sizes, using the thin bed model, indicate the importance of detector size, especially length, to this parameter. The smallest detector tested was 1.0 inch x 2 inch, and it is encouraging to note that the measured α values for this detector show the best agreement with the α calculated assuming an infinitesimally small detector.

The theoretically predicted geologic impulse function given in equation (4) accurately represents the measured shape over the range of about $\pm$30 cm from the thin bed location. For distances from the thin bed greater than $\pm$30 cm, the measured responses for all but the 1.5 inch x 9 inch detector are greater than predicted, rising above the exponential asymptotic dependence. The 1.5 inch x 9 inch detector response follows the exponential relation almost exactly. However, the geologic impulse parameter α is strongly affected by detector size and shape, and it will have to be determined experimentally until proper account of detector response can be included in the theoretical calculations.

RESOLUTION OF THIN URANIUM BEDS

Inverse Filter Log Deconvolution Technique

This approach to log deconvolution is based on the theory of digital time series analysis. Given appropriate functions to describe the logging probe response to thin zones of potassium, uranium, and thorium, this theory predicts an inverse discretized (digital) filter that, when applied to the spectral gamma-ray log, yields potassium, uranium, or thorium distributions with depth.

Conaway has applied this method (Reference 6) using the two sided exponential function of equation (3) to describe the geologic impulse function. The function is realistic only for very small detectors or for detectors whose length is much less than $1/\alpha$. Conaway has shown that the inverse digital filter corresponding to equation (3) is given by the triad

$$\frac{-1}{(\alpha\Delta z)^2} \quad , \quad 1 + \frac{2}{(\alpha\Delta z)^2} \quad , \quad \frac{-1}{(\alpha\Delta z)^2} \tag{5}$$

where Δz is the depth interval utilized for the digital gamma-ray log and α is the geologic impulse parameter. Since the filter does not account for finite detector length, the sampling interval Δz must be no smaller than the detector's length. The successful deconvolution of gamma-ray logging data with the inverse filter technique depends on the correct choice for the parameter α. In addition, the data must ideally be free of noise since the introduction of noise (e.g. uncertainties from counting statistics) degrades the deconvolution.

Spectral Gamma-Ray Log of Layered Uranium Zones

The Grand Junction borehole model N5 consists of several horizontal uranium zones with differing grades and thicknesses. The model was logged statically at 0.1 foot depth intervals using a 2 inch diameter probe containing a 1.5 inch x 3 inch detector. The detector was surrounded by a 0.125 inch lead filter to reduce the detection rate for low energy gamma rays, and the probe was calibrated with the lead filter in place using the thick ore zones of the K, U, and Th models. Apparent uranium grades were computed for each depth within model N5 using the resulting calibration. The apparent uranium grade versus depth is plotted in semilogarithmic form as "dots" in Figure 10. The grade is labeled "apparent" because the static log has not yet been deconvolved to remove the effect of the geologic impulse response.

Deconvolution of Spectral Gamma-Ray Log of Model N5

The apparent grade versus depth log presented in Figure 10 has been deconvolved with the inverse filter in equation (5). In the absence of bulk density data for model N5, the best estimate that one can make for α is to assume the same density as the U model and to employ the average obtained from the U model differential profile. This value of 0.112 cm^{-1} was decreased slightly to 0.108 cm^{-1} to account for the effect of the lead filter, as determined from thin bed measurements. When converted to units of inverse feet, the α estimated for model N5 is 3.3 $feet^{-1}$. The inverse digital filter in equation (5) was computed for an α value of 3.3 $feet^{-1}$ and for a depth interval Δz of 0.3 feet to insure a sampling interval greater than detector length. When this inverse filter was applied to the data from 0.3 foot intervals, the deconvolved result tended to be negative under certain conditions (e.g., when the apparent grade rose rapidly from near zero to very large values).

The parameter α was varied in steps of 0.1 $feet^{-1}$ to obtain better deconvolution results. For each new value of α the apparent grade versus depth data were again deconvolved with the inverse filter. The value of 3.6 $feet^{-1}$ gave the best agreement with the assigned grade versus depth of the model, and it showed the best definition of the thin barren zone at 9 feet without giving negative results. The deconvolved results for α = 3.6 $feet^{-1}$ are plotted in Figure 10 along with the assigned grade versus depth (shaded region) of the model. The action of the filter is quite dramatic and shows an unidentified, low-grade uranium zone beginning with 25 ppm at 6.1 feet and increasing to 210 ppm at 7.3 feet. The shape of the static log

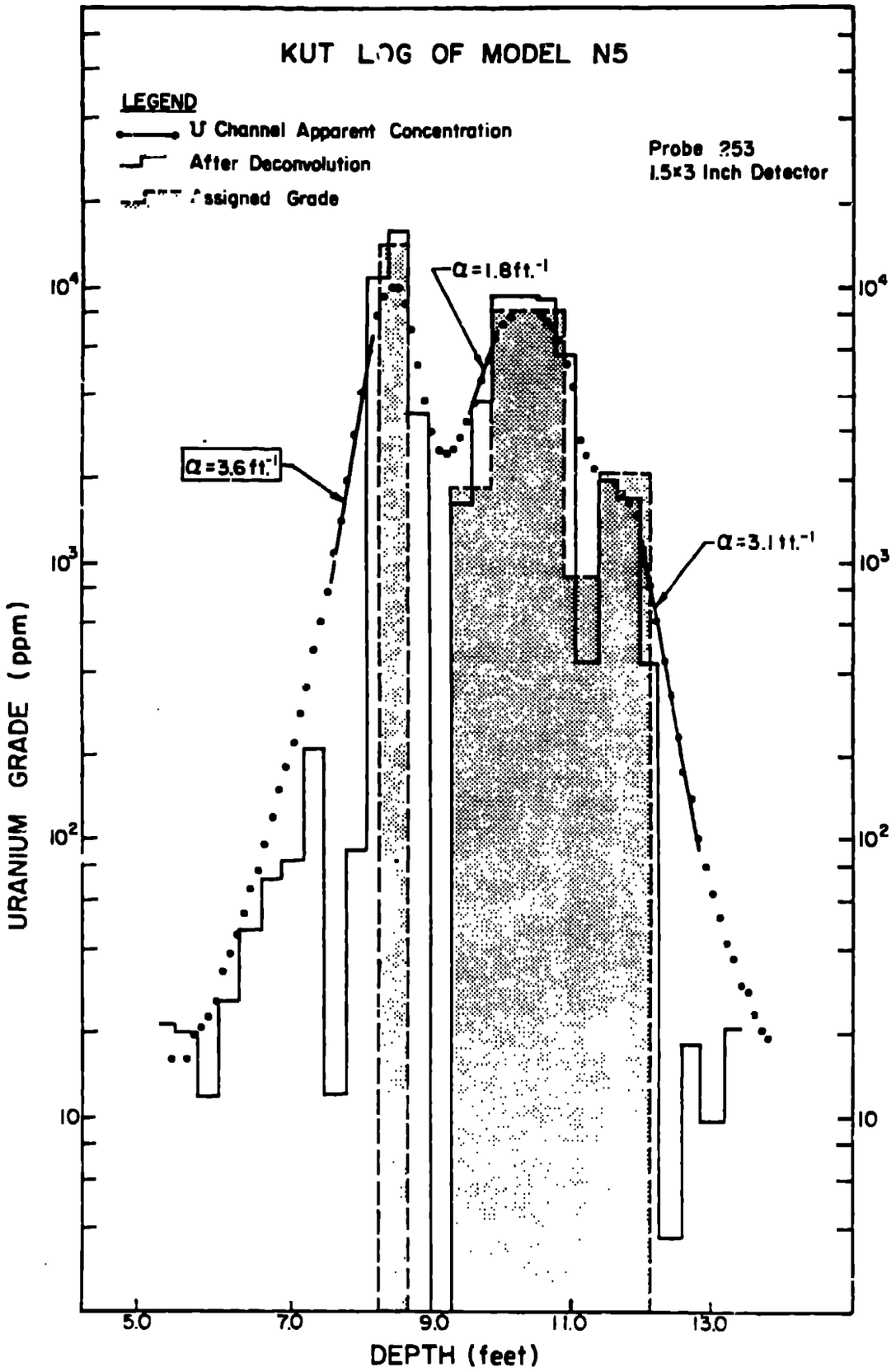

KUT LOG OF MODEL N5
LEGEND
U Channel Apparent Concentration
After Deconvolution
Assigned Grade
Probe 253
1.5x3 Inch Detector
α=1.8ft.⁻¹
α=3.6ft.⁻¹
α=3.1ft.⁻¹
URANIUM GRADE (ppm)
10⁴
10³
10²
10
5.0
7.0
9.0
11.0
13.0
DEPTH (feet)

Figure 10

(dots) between 7.5 and 8.2 feet provides support for the choice of 3.6 $feet^{-1}$ for α. Since this region is near the interface between a high grade ore zone and nearly barren zone, the semilogarithmic plot should contain a linear portion whose slope is the parameter α. The computed slope is 3.6 $feet^{-1}$, in agreement with the value obtained by varying α until the best agreement with assigned grade was obtained. The 10 percent difference in α is probably due to a bulk density or composition difference between models U and N5.

Also shown in Figure 10 are α estimates computed from other portions of the static log where the semilogarithmic plot is linear. The value of 1.8 $feet^{-1}$ obtained between 9.5 and 10 feet is clearly too low. This value was included to illustrate the fact that only near the interface between two zones of highly different grade can one hope to obtain a linear slope that is close to α. Furthermore, one of the two zones should be completely barren of uranium to prevent giving α estimates that are too small.

Summary of Inverse Filter Log Deconvolution

A static spectral gamma-ray log of a layered uranium model was obtained with a 1.5 inch x 3 inch detector, and the log was successfully deconvolved using the inverse digital filter technique. The value of the parameter α required for the most satisfactory deconvolution was 3.6 $feet^{-1}$ (0.118 cm^{-1}). This value is 10 percent higher than the α estimate for this detector based on the thin bed measurements. The filter parameter α was also estimated directly from the plot of the static log. The resulting value was in excellent agreement with that obtained by the trial and error variation of α to obtain the best agreement with assigned grade versus depth.

The principal advantage of the inverse digital filter deconvolution technique over existing methods seems to be that it is very fast and provides the capability to deconvolve field logs in nearly "real-time" with the use of modest computing capability. Deconvolution in the field may require that the parameter be dynamically adjusted to account for varying borehole and formation conditions. Conaway (Reference 6) has suggested that a technique for determining α dynamically in the field is to observe the slope of the semilogarithmic display of stripped K, U, or Th window concentrations when ore zone/barren zone interfaces are encountered. This may prove to be a feasible field technique, but the static log results presented here show that only when the grade changes by at least three orders of magnitude at the interface will the linear slope of the semilogarithmic interface response be a good measure of α.

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For the bibliography and photos of the authors see the preceding report "Spectral Gamma-Ray Logging II: Borehole Correction Factors."